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SHORT NOTES

LOCATING EARTHQUAKES WITH AMPLITUDE: APPLICATION TO REAL-TIME SEISMOLOGY

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Earthquakes are traditionally located using travel times. However, since the ground-motion amplitude generally decays with the distance from the source, it should also be possible to locate earthquakes using amplitude data. Amplitudes are affected by many factors other than the distance, so that we do not expect to be able to locate the epicenter, the location of the initial rupture, very accurately with amplitude data. However, locating earthquakes with amplitudes has its own merits: (1) For postearthquake emergency services, it is often more important to know the spatial distribution of strong-motion parameters such as peak acceleration and peak velocity than the rupture initiation point itself (National Research Council, 1991). This is especially true for thrust earthquakes (e.g., 1971 San Fernando earthquake; 1987 Whittier Narrows earthquake) or events with large rupture zones. (2) The amplitudes are usually much easier to determine than the arrival times, especially for events with complex rupture patterns or with immediate foreshocks in which event association can be difficult. For application to real-time earthquake information systems such as CUBE (Caltech/USGS Broadcast of Earthquakes; Kanamori *et al.*, 1991), the amplitude method could provide a quick and robust way to send useful information for emergency operations. Here, we report a few examples and propose a method for future implementation in a CUBE-type system.

We use peak acceleration as the amplitude parameter. However, use of other parameters such as peak velocity and CAV (EPRI, 1991) is equally possible. For simplicity, we use the peak acceleration-distance relation developed by Joyner and Boore (1981) to fit the observed data. This relation is given by

$$\log A = -1.02 + 0.249M - \log(d^2 + 7.3^2)^{1/2} - 0.00255(d^2 + 7.3^2)^{1/2}, \quad (1)$$

where A is the peak horizontal acceleration in g, M is magnitude, and d is the closest distance to the surface projection of the fault rupture in km. In our application, d is interpreted as the distance between the site and the "strong-motion centroid" (SMC) that is to be determined from the amplitude data. Since d is defined differently from Joyner and Boore (1981), the meaning of the magnitude M is also different.

We fit the observed peak acceleration data with equation (1) and determine M, latitude (ϕ), and longitude (λ) of the SMC. Equation (1) is nonlinear with respect to ϕ and λ. We scan the model parameter space (M, ϕ, λ) to determine the approximate location of the global minimum of the error function. Then we use the values of M, ϕ, and λ at that location as the first approximation to determine the final solution using the method of least-squares. This procedure is especially important for spotting an event located outside the network.

We tested this method using the data for the 1989 Loma Prieta, 1991 Sierra Madre, 1992 Joshua Tree, 1992 Landers, and 1992 Big Bear earthquakes. The data used and the results are summarized in Table 1. Figure 1a shows the

TABLE 1

DETERMINATION OF STRONG-MOTION CENTROID WITH PEAK ACCELERATION

Data Set	M	Latitude (°)	Longitude (°)	RMS (% of g)
1992 Landers Earthquake (M_w = 7.3, ϕ = 34.22°, λ = −116.43°)				
TERRAscope (6)*	7.93	34.46	−116.90	0.37
TERRAscope + SCSN FBA (13)	7.98	34.38	−116.61	2.5
All data (76)†	8.86	34.57	−116.45	3.2
Prediction by TERRAscope				5.1
Prediction by Ts + FBA				
1992 Big Bear Earthquake (M_w = 6.4, ϕ = 34.21°, λ = −116.83°)				
TERRAscope (6)	6.00	34.09	−116.96	0.11
TERRAscope + SCSN FBA (12)	6.67	34.04	−116.90	1.29
All data (23)†	7.63	34.22	−116.82	4.3
Prediction by TERRAscope				10.5
Prediction by Ts + FBA				9.4
1992 Joshua Tree Earthquake (M_w = 6.1, ϕ = 33.94°, λ = −116.34°)				
TERRAscope (6)	5.81	34.08	−116.33	0.14
TERRAscope + SCSN FBA (11)	6.24	34.14	−116.21	0.37
All data (31)†	7.39	33.97	−116.27	6.05
Prediction by TERRAscope				13.44
Prediction by Ts + FBA				
1991 Sierra Madre Earthquake (M_w = 5.5, ϕ = 34.26°, λ = −118.00°)				
TERRAscope (6)	4.63	34.02	−118.04	0.12
TERRAscope + SCSN FBA (10)	5.41	34.13	−118.07	4.3
All data (101)†	5.98	34.19	−118.05	3.6
Prediction by TERRAscope				
Prediction by Ts + FBA				
1989 Loma Prieta Earthquake (M_w = 6.9, ϕ = 37.04°, λ = −121.88°)				
All data (129)‡	8.21	36.97	−121.84	10.0

*Numbers in the parentheses indicate the number of stations used.
†TERRAscope, SCSN FBA, and CDMG stations.
‡TERRAscope, SCSN FBA, CDMG, and USGS stations.

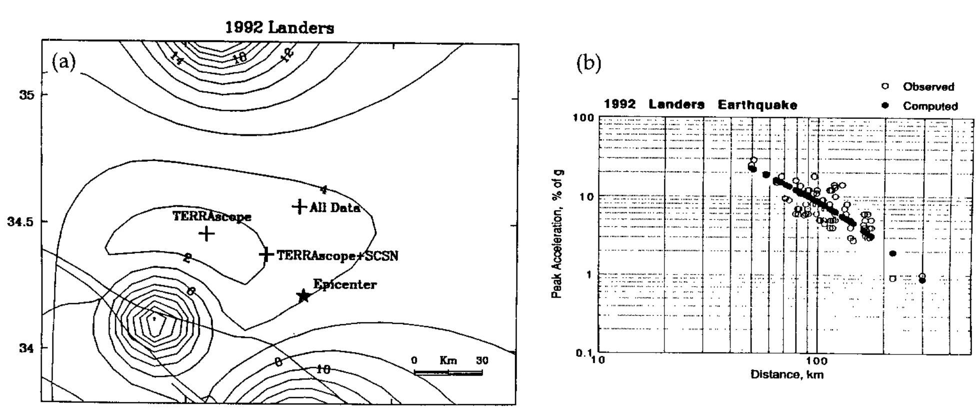

FIG. 1. (a) The epicenter (star) and the strong-motion centroid (SMC, + symbol) of the 1992 Landers earthquake, determined with data from TERRAscope, TERRAscope + SCSN, and all the stations including those of the California Division of Mines and Geology. The contour lines indicate the errors when only TERRAscope stations are used. (b) The fit of equation (1) with the data when all the data are used.

results for the 1992 Landers earthquake. The contour lines show the topography of the error function, when only TERRAscope data are used. Figure 1b shows the fit with the data. Figures 2a to d show the results for the other events. Contour lines are not shown in these figures to avoid clutter. As shown in Figure 1, the SMC determined from the amplitude data is, in general, very close to the epicenter determined from travel times. Even when only six TERRAscope stations are used, the SMC is located fairly close to the epicenter. For the Landers earthquake, the SMC location using all the data is about 40 km north of the epicenter, which is reasonable considering the 70-km fault extending north from the epicenter.

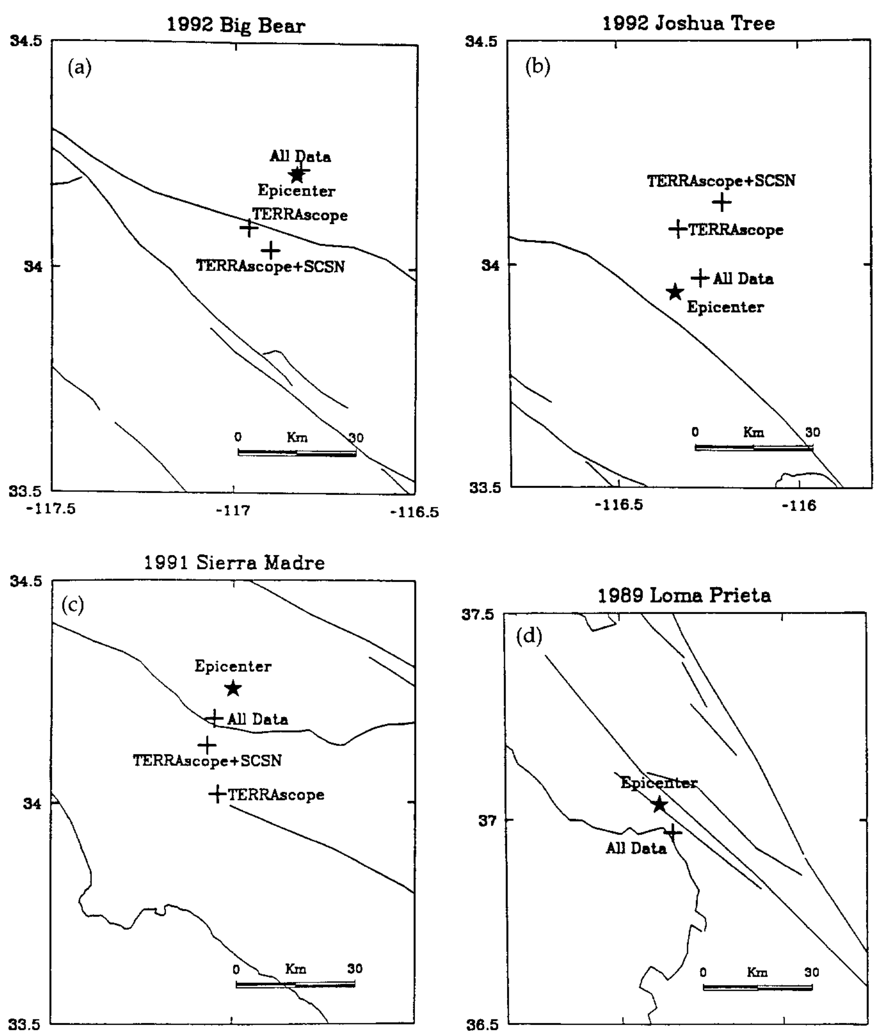

FIG. 2. (a) The epicenter (star) and the strong-motion centroid (SMC, + symbol) of the 1992 Big Bear earthquake determined with the data from TERRAscope, TERRAscope + SCSN, and all the stations including those of the California Division of Mines and Geology. (b) Same as (a). The 1992 Joshua Tree earthquake. (c) Same as (a). The 1991 Sierra Madre Earthquake. (d) The epicenter (star) and the strong-motion centroid (SMC, + symbol) of the 1989 Loma Prieta earthquake, determined with data from the stations of the California Division of Mines and Geology and the U.S. Geological Survey.

An important application of this method is real-time estimation of strong motions. If some strong-motion data are available in near real-time, we can locate the SMC with this method quickly and then estimate strong-motion distribution using equation (1). To illustrate this, we performed the following experiment. In southern California, six TERRAscope stations provide near-real time ground-motion data. Also, several accelerographs are installed in the Southern California Seismic Network (SCSN), from which near real-time data are available through analog telemetry. Using the peak acceleration data for the 1992 Landers earthquake obtained from the six TERRAscope stations, we located the SMC (Fig. 1a), estimated the peak accelerations at all other strong-motion instrument sites of SCSN and the California Division of Mines and Geology (CDMG), and compared them with the observed. Figure 3 shows the results. Even if only six sparse TERRAscope stations are used, we can predict strong motions over a large area of southern California very well. The strong motion sites of SCSN and CDMG cover the area that includes San Bernardino, Riverside, Palmdale, and Los Angeles. The RMS (root-mean-square) error is 5.1% of g. This result suggests that if a sufficiently large number (e.g., 30) of telemetered stations are available, we can make good real-time estimations of strong ground motions. As mentioned earlier, the method uses only amplitude data and is very simple to implement in a real-time seismic system.

When more real-time data become available, further considerations may be given to: (1) strong-motion parameters other than peak acceleration, (2) noncircular distribution of strong-motion parameters for elongated sources, (3) station corrections, and (4) nonlinear site response.

The values of M listed in Table 1 differ significantly from those assigned to these earthquakes. This difference is largely due to the difference in the definition of d. Since the geometry and size of the fault plane are unknown immediately after the occurrence of an earthquake, we cannot use d defined by

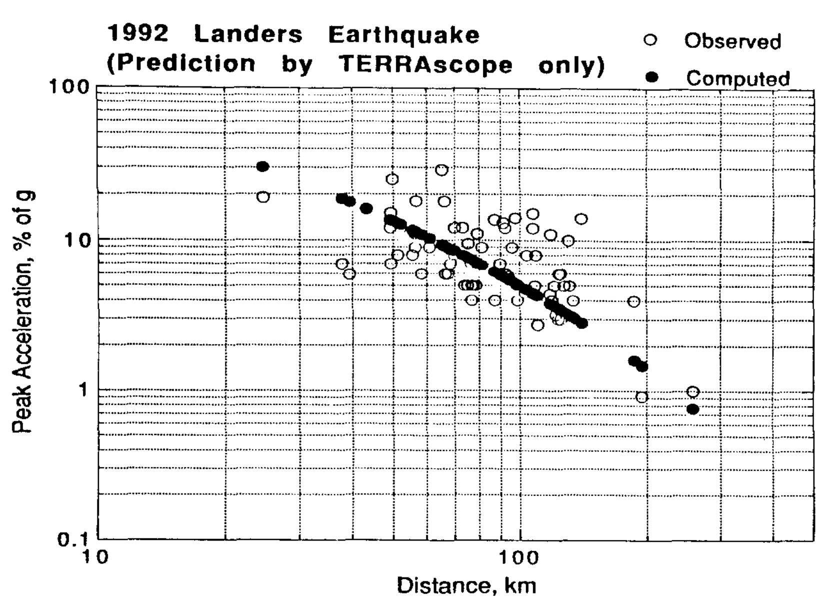

FIG. 3. Comparison of the observed peak accelerations with those predicted with only TERRAscope data.

Joyner and Boore (1981). Thus, *M* in Table 1 should be regarded as a scaling constant and should not be given much significance. For most strong-motion applications, however, what is really needed are strong-motion parameters, rather than the earthquake magnitude. In a way, our method side-steps the ordinary seismological parameters such as the magnitude, depth, mechanism, and rupture directivity, which are not necessarily the parameter of immediate interest for emergency services.

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